Chapter 4
Geotechnical Explorations for Tunnels and Shafts

4-1. General

a. Geological, geomechanical, and hydrological factors more than any other factors determine the degree of difficulty and cost of constructing an underground facility. Chapter 3 of this Manual discusses many of the geological factors that affect underground works. This chapter presents guidelines for acquiring the necessary geological data for the planning, design, and construction of underground works.

b. In brief, the types of information that must be obtained can be classified as follows:

- Geologic profile (stratigraphy, structure, and identification of principal rock types and their general characteristics).

- Rock mass characteristics and geomechanical properties.

- Hydrogeology (groundwater reservoirs, aquifers, and pressures).

- Exposure to construction risk (major water-bearing faults, methane gas, etc.).

c. USACE's Engineer Manual 1110-1-1804, Geotechnical Investigations, and EM 1110-1-1802, Geophysical Exploration, contain information useful for the planning and execution of geotechnical explorations for tunnels and shafts.

4-2. Explorations for Reconnaissance and Feasibility Studies

a. *General*. The project is conceived, defined, and broadly scoped out during the reconnaissance phase. Geotechnical information required during this phase is obtained almost exclusively from existing data, with a minimum of field work. More information is required to conduct feasibility studies. Here the emphasis is first on defining the regional geology and the basic issues of design and construction. Methods of data acquisition include at least the following:

- Available data acquisition and study.

- Remote sensing.

- Preliminary geologic field mapping.

- Geophysical explorations if appropriate.

- Selected exploratory borings in critical locations.

b. *Sources of available information*.

(1) Topographic maps are available for every location in the United States. They are useful in showing geologic domains and often, by interpretation, show geologic structures. Geologic maps are also available for virtually every location in the United States. These may be obtained from the U.S. Geologic Service (USGS), state geologic services, university publications, or private sources such as mining companies. Some private information is proprietary and may not be available for use.

(2) In urban areas and where site improvements have been made (e.g., highways), private and public owners will frequently have information about past geotechnical and geologic investigations. Local geotechnical firms regularly maintain files of such information.

(3) Much of the available information will have been collected for purposes other than engineering evaluations (e.g., resource assessments), and interpretive work is required of the engineering geologist to extract the information that is useful for tunnel and shaft design and construction. The end product of office studies is a set of geologic maps and profiles, descriptions of rock types, and a list of potential difficulties, all subject to field verification or verification by other means.

(4) Case histories of underground works in the region, or in similar types of rock, are sometimes available and are very useful additions to the geotechnical database.

(5) The collection and analysis of available data must also include geographical, cultural, and environmental data, such as land ownership, existing facilities, access routes, environmental sensitivity, etc. Local resource developments, such as quarries, mines, or oil wells, should also be mapped.

c. *Remote sensing techniques*.

(1) Every location in the United States has been photographed from the air at least once and many locations numerous times, and most of these air photos are available at a low cost, from private or public sources. The typical

black-and-white stereo coverage usually used for topographic mapping is very well suited for geologic interpretation and will divulge details such as landform definition, boundaries between rock and soil types, lineaments, landslides, drainage features, archaeological sites, etc. Color photos are useful for land use determination. False-color photos are used for special purposes. Infrared photos show temperature differences and are useful, for example, in defining moisture content contrasts of the ground, as well as drainage paths.

(2) In built-up areas, air photos cannot show much of the natural ground, but it is often possible to find older photos from the time before construction. A series of older sets of photos sometimes are handy for tracing the past history of a locality. Satellite coverage is now available from public sources (and some private sources) in many forms and to many scales, and made for many purposes. Aerial photography is used to supplement existing mapping data and to identify additional geologic features, useful for field verification and for planning additional site exploration work. Air photos are also useful for overlaying alignment drawings.

d. Field mapping.

(1) Initial onsite studies should start with a careful reconnaissance over the tunnel alignment, paying particular attention to the potential portal and shaft locations. Features identified on maps and air photos should be verified. Rock outcrops, often exposed in road cuts, provide a source for information about rock mass fracturing and bedding and the location of rock type boundaries, faults, dikes, and other geologic features. In particular, the field survey should pay attention to features that could signify difficulties:

- Slides, new or old, particularly in portal areas.
- Major faults.
- Sinkholes and karstic terrain.
- Hot springs.
- Volcanic activity.
- Anhydrite, gypsum, or swelling shales.
- Caves.
- Stress relief cracks.
- Zones of deep weathering or talus.

(2) Once alignment and portal site alternatives have been set, a detailed geologic mapping effort should be carried out. Joints, faults, and bedding planes should be mapped and their orientations plotted by stereographic projection so that statistical analysis can be performed (often, today, with computer assistance). Predominant joint systems, and their variations along the alignment, can be determined in this way. Based on surface mapping, the geologist must then project the geologic conditions to the elevation of the proposed underground structures so that tunneling conditions can be assessed.

e. Hydrogeology.

(1) Groundwater has the potential to cause great difficulties for underground work, and a special effort should be made to define the groundwater regime—aquifers, sources of water, water quality and temperature, depth to groundwater. A hydrological survey is necessary to ascertain whether tunnel construction will have a deleterious effect on the groundwater regime and the flora and fauna that depend on it. Maps and air photos, including infrared, will help define the groundwater conditions. Mapping of permanent or ephemeral streams and other water bodies and the flows and levels in these bodies at various times of the year is usually required. Proximity of the groundwater table may be judged by the types of vegetation growing on the site.

(2) As a part of the hydrogeological survey, all existing water wells in the area should be located, their history and condition assessed, and groundwater levels taken. Additional hydrogeological work to be carried out at a later stage includes measurements of groundwater levels or pressures in boreholes, permeability testing using packers in boreholes, and sometimes pumping tests.

f. Geophysical explorations from the ground surface.

(1) Geophysical methods of exploration are often useful at the earlier stages of a project because they are relatively inexpensive and can cover relatively large volumes of geologic material in a short time. Details on the planning and execution of geophysical explorations can be found in EM 1110-1-1802.

(2) The most common geophysical explorations carried out for underground works are seismic refraction or reflection and electric resistivity surveys. Seismic

explorations can measure the seismic velocity of underground materials and discover areas of velocity contrasts, such as between different kinds of rock or at fault zones. They are also useful in determining the elevation of the groundwater table.

(3) Seismic velocity is taken as a measure of rock quality and often used to assess rippability of the rock by ripper-equipped dozers. If there is no seismic velocity contrast across a boundary, the boundary will remain invisible to the seismic exploration.

(4) Depending on the energy applied in the seismic work and the particular technique, seismic explorations can be designed for shallow work with high resolution and for deep explorations with a lower resolution. Deep seismic explorations, using sophisticated computer enhancement of the signals, are regularly employed in the petroleum industry.

(5) Electrical resistivity measurements use arrays of power source and measurement points and provide an image of resistivity variations in the ground. These measurements are usually used to determine the depth to groundwater.

g. Additional explorations during feasibility studies. It is often appropriate to conduct initial field explorations in the form of borings or trenching at this early stage, primarily to verify the presence or location of critical geologic features that could affect the feasibility of the project or have a great effect on the selection of tunnel portals.

4-3. Explorations for Preconstruction Planning and Engineering

a. General.

(1) During the engineering design phases, explorations must be carried out to acquire data not only for the design of the underground structures but also for their construction. For this reason, exploration programs for underground works must be planned by engineering geologists or geotechnical engineers in close cooperation with designers and construction engineers.

(2) Most geotechnical data for design are obtained during preconstruction planning and engineering, but supplemental explorations, as well as explorations and testing for purposes of construction, may be carried out in the later design stage.

b. Environmental and geologic data requirements.

(1) The specific environmental data needs for a particular underground project very much depend on the geologic and geographic environment and the functional requirement of the underground facility. Some generalities can be stated, however, presented here in the form of a checklist:

- Existing infrastructure; obstacles underground and above.
- Surface structures within area of influence.
- Land ownership.
- Contaminated ground or groundwater.
- Naturally gassy ground or groundwater with deleterious chemistry.
- Access constraints for potential work sites and transport routes.
- Sites for muck transport and disposal.
- Legal and environmental constraints, enumerated in environmental statements or reports or elsewhere.

(2) As earlier noted, required geologic data include the geologic profile, rock and rock mass properties, hydrogeology, and exposure to geologic hazards. After initial fact finding and mapping, it is often possible to divide the tunnel alignment into zones of consistent rock mass condition. Criteria for zonation would be site specific, but factors involving intact rock, rock mass, and excavation system characteristics should be considered. Each zone should be characterized in terms of average expected condition as well as extreme conditions likely to be encountered.

(3) Initial literature work and mapping should identify major components of the stratigraphy and the geologic structure, which form the framework for zonation of the alignment and for the planning of the explorations. An appropriate rock mass classification scheme should be selected and all data necessary for the use of the classification system obtained. During construction, a more simplified system may be established that can be used by field people with little delay in the daily construction routine.

(4) Particular attention should be given to the following types of information:

- Top of rock; depth of weathered rock.
- Water bearing zones, aquifers, fault zones, and caves.
- Karstic ground conditions.
- Very strong (>250 MPa) and very abrasive material that can affect TBM performance.
- Highly stressed material with potential for overstress.
- Potential for gases.
- Corrosive groundwater.
- Slake-susceptible material and material with potential for swell.
- Material otherwise affected by water (dissolution, swell).
- Zones of weak rock (low intact strength, altered materials, faulted and sheared materials).

c. Strategies for exploration.

(1) Because of the complexities of geology and the variety of functional demands, no two tunnels are alike. It is therefore difficult to give hard and fast rules about the required intensity of explorations or the most appropriate types of exploration. Nonetheless, some common-sense rules can help in the planning of explorations.

(a) Plan explorations to define the best, worst, and average conditions for the construction of the underground works; locate and define conditions that can pose hazards or great difficulty during construction.

(b) Use qualified geologists to produce the most accurate geologic interpretation so as to form a geologic model that can be used as a framework to organize data and to extrapolate conditions to the locations of the underground structures.

(c) Determine and use the most cost-effective methods to discover the information sought (e.g., seismic refraction to determine top of rock).

(d) Anticipate methods of construction and obtain data required to select construction methods and estimate costs (e.g., data to estimate TBM performance and advance rates).

(e) Anticipate potential failre modes for the completed structures and required types of analysis, and obtain the necessary data to analyze them (e.g., in situ stress, strength, and modulus data for numerical modeling).

(f) Drill at least one boring at each shaft location and at each portal.

(g) Special problems may require additional explorations (e.g., to determine top of rock where there is a potential for mixed-face tunneling conditions or to define the extent of a pollutant plume).

(2) The complexity and size of an underground structure has a bearing on the required intensity of explorations. A long tunnel of small diameter does not warrant the expense of detailed explorations, and a tunneling method able to cope with a variety of conditions is required. On the other hand, a large underground cavern, such as an underground power house or valve chamber is more difficult to construct and warrants detailed analyses that include closely spaced borings, reliable design data, and occasionally a pilot tunnel.

(3) Frequently, even the most thorough explorations will not provide sufficient information to anticipate all relevant design and construction conditions. This happens, for example, in deposits of alluvial or estuarine origin, or in badly folded and faulted rock. Here, the variation from point to point may be impossible to discover with any reasonable exploration efforts. In such instances, the design strategy should deal with the average or most commonly occurring condition in a cost-effective manner and provide means and methods to overcome the worst anticipated condition, regardless of where it is encountered.

(4) In mountainous terrain, it is often difficult or very expensive to gain access to the ground surface above the tunnel alignment for exploratory drilling. Many tunnels have been driven with borehole data available only at the portals. In such instances, maximum use must be made of remote sensing and surface geologic mapping, with geologic extrapolations to tunnel depth. The tunnel must be designed to deal with postulated worst-case conditions that may never actually be encountered. The strategy may also include long horizontal borings drilled from the portals or probeholes drilled from the face of the advancing tunnel.

Horizontal boreholes up to 540 m (1,800 ft) long were drilled from one portal for the Cumberland Gap (Tennessee, Kentucky) highway tunnel. For the Harlan diversion tunnels in Kentucky, the USACE employed horizontal borings up to 360 m (1,080 ft) long.

(5) It may also be difficult or expensive to obtain borehole data for tunnels under rivers and beneath lakes and the ocean. A minimum of borings should still be drilled, even if costly, but maximum use should be made of subbottom profiling. For the Boston Effluent Outfall Tunnel, borings were drilled offshore about every 300-400 m (1,000-1,300 ft), and heavy use was made of seismic refraction profiling as well as deep digital reflection, at a cost of exploration approaching 10 percent of construction cost. Where large openings are required in difficult geology, pilot tunnels are often warranted.

(6) The question is frequently argued of how much information must be obtained for the design of an underground structure. The simple answer can be stated in terms of cost-effectiveness: If the next boring does not add knowledge that will reduce construction cost an amount equal to the cost of the boring, then sufficient information has already been obtained. In practice, this assessment is not so simple, because the results of the next boring, by definition, are unknown, and the construction cost saving can be assessed only on a very subjective basis.

(7) The intensity of explorations can be measured in several meaningful ways:

- Cost of full geotechnical exploration program (borings, testing, geophysics) as percentage of construction cost.
- Typical spacing of boreholes.
- Number of meters of borehole drilled for each 100 m of tunnel.

(8) The required intensity of explorations will vary at least with the following factors: complexity of geology, project environment, depth of tunnel, end use requirements of the tunnel, accessibility for explorations, and relative cost of individual borings.

(9) A practical guide for assessing the suitability of an exploration program is shown in Table 4-1. The guide starts with a relatively simple base case and employs factors up or down from there. The base case considered is a 6-m (20-ft) drainage tunnel through moderately complex geology in a suburban area at a moderate depth of about 30 m (100 ft).

d. Exploratory borings.

(1) Tools and methods for exploratory borings and sampling are described in detail in EM 1110-1-1804. The most common sample size used for core borings for underground works is the NX-size, of approximately 2-in. diam.

(2) For deep boreholes, it is common to use wireline drilling. With this method of drilling, a large-diameter drill stem is used, furnished at the bottom end with a suitable carbide or diamond bit. The core barrel is lowered to the bottom by a wireline and snaps into the drill bit while coring takes place. When a core run is finished, the core barrel is reeled up and the core withdrawn from the barrel. With this method, time-consuming trips in and out of the hole with the entire drill string are avoided. At the same time, the drill string provides borehole stability.

Table 4-1
Guidelines for Assessing Exploration Needs for Tunnels and in Rock

	Cost of Borings and Testing, % of Construction	Borehole Spacing	Borehole Length per 100 m Tunnel
Base case	0.4-0.8	150-300 m	15-25 m
Extreme range	0.3-10	15-1,000 m	5-1,000 m
For conditions noted, multiply base case by the following factors:			
Simple geology	0.5	2-2.5	0.5
Complex geology	2-3	0.3-0.5	2-3
Rural	0.5	2-2.5	0.5
Dense urban	2-4	0.3-0.4	2-5
Deep tunnel	0.8-1	Increase borehole spacing in proportion to depth of tunnel	
Poor surface access	0.5-1.5	5-10+	variable
Shafts and portals	NA	At least one each	NA
Special problems	1.5-2	0.2-0.5 locally	variable

(3) On occasions, core is extracted only from around the elevation of the underground structure; the remainder of the hole drilled blind, i.e., without core. Usually, however, the entire length of core is of geological interest and should be recovered. If a full sweep of downhole geophysical tools is run in the hole, geologic correlation between holes is usually possible, and core may be needed only at the depth of the underground structure.

4-4. Testing of Intact Rock and Rock Mass

a. General. Laboratory tests provide a quantitative assessment of the properties of intact rock specimens. Laboratory tests do not necessarily represent the properties of the rock mass in situ, which are affected by joints, bedding planes, and other flaws that are not present in the laboratory specimens. In addition, mechanisms of behavior tested in the laboratory do not always represent the mechanisms of behavior experienced in situ. Nonetheless, laboratory testing provides indices and clues to in situ behavior, as well as data for comparison and correlation with experience records. Determination of properties representative of in situ conditions and of the undisturbed rock mass may require in situ testing.

b. Tests in boreholes and trial excavations.

(1) A number of properties can only be measured by in situ tests, either in boreholes or in trial excavations or tunnels. Standardized procedures for in situ tests are published by the American Society for Testing and Materials (ASTM) and as recommendations of the International Society of Rock Mechanics, and in the Rock Testing Manual.

(2) The most common in situ tests performed for underground works are listed in Table 4-2.

Table 4-2
Common Test Methods

Parameter	Test Method
In situ stress state	U.S. Bureau of Mines Borehole Deformation Gage Hydraulic fracturing Overcoring of hollow inclusion gage
Modulus of deformation	Rigid plate loading test Flexible plate loading test Flatjack test Radial jacking test Diametrically loaded borehole jack Pressuremeter (soft rock)
Shear strength	Torsional shear test Direct shear test Pressuremeter (soft rock)
Permeability	Constant head injection test Pressure pulse technique Pumping tests

(3) Permeability tests are performed using packers to isolate intervals in boreholes; double packers insulating 10 or 20 ft (3 or 6 m) of borehole are usually used. Sometimes single packer tests are performed, isolating the lower part of the borehole. Permeability tests should be performed in every borehole wherever groundwater is a potential problem. Other tests conducted in boreholes can be performed reasonably inexpensively, while those performed in test trenches or pilot tunnels tend to be expensive.

(4) In many cases a suite of downhole geophysics surveys are also run in boreholes in rock. EM 1110-1-1802 describes the common downhole geophysical surveying techniques. A common combination of surveys performed includes the following:

- Caliper log to measure the borehole diameter and locate washouts.
- Electric resistivity to measure variations of the resistivity of the rock mass.
- Spontaneous potential to measure the potential difference between an underground location and a reference location.
- Natural gamma to measure gamma emissions from radioactive materials in the ground.

(5) Other downhole survey techniques can provide images of the borehole wall (gyroscopically controlled) and information about the density, porosity, or seismic velocity of the rock. Seismic methods using boreholes include cross-hole (hole-to-hole) methods as well as methods using a source at locations at the ground surface with geophones in the borehole, or vice versa.

c. Tests performed in the laboratory. Test procedures and standards for rock tests in the laboratory are specified in ASTM Standards, Recommendations of the International Society of Rock Mechanics, and in the Rock Testing Handbook. Some of these tests can be characterized as index tests, used mostly for correlation and comparison, while others directly measure properties important to behavior. The tests most commonly performed in the laboratory for underground works are listed in Table 4-3.

Table 4-3
Tests Performed in Laboratory

Rock Property	Parameter/Characterization
Index properties	Density Porosity Moisture content Slake durability Swelling index Point load index Hardness and abrasivity
Strength	Uniaxial compressive strength Triaxial compressive strength Tensile strength (Brazilian) Shear strength of joints
Deformability	Young's modulus Poisson's ratio
Time dependence	Creep characteristics
Permeability	Coefficient of permeability
Mineralogy and grain sizes	Thin-sections analysis Differential thermal analysis X-ray diffraction

d. Use of test data. The following indicates some particular uses of tests and test data.

(1) Rock variability.

(a) Index tests.

(b) Point load tests.

(2) Stability in homogeneous rock.

(a) Unconfined compressive strength.

(b) In situ stress.

(3) Stability in jointed rock.

(a) Rock mass index data (see later).

(b) Unconfined compressive strength.

(c) Joint shear strength.

(d) In situ stress.

(4) Groundwater flow and pressure.

(a) In situ permeability.

(b) In situ water pressure.

(c) Porosity.

(d) Pumping test data.

(5) Sensitivity to atmospheric exposure and water content change.

(a) Slake durability test.

(b) Swelling index.

(c) Density.

(d) Moisture content.

(e) Mineralogy.

(6) Computer modeling.

(a) In situ stress.

(b) Young's modulus.

(c) Poisson's ratio.

(d) Uniaxial and triaxial strength data.

(7) TBM performance (see Appendix C for details).

(a) Uniaxial compressive strength.

(b) Tensile strength.

(c) Hardness and abrasivity.

(d) Mineralogy.

e. Rock mass classification systems.

(1) Rock mass classification systems for engineering purposes use experience derived from previous projects to estimate the conditions at a proposed site. These systems combine findings from observation, experience, and engineering judgment to provide an empirically based, quantitative assessment of rock conditions. For a classification system to be successful, the parameters must be relevant to their application and be capable of being consistently rated against some set of standard descriptions or objective set of rules on the basis of simple observations or measurements.

(2) The diversity of classifications of rock material, rock mass, and rock structure used in geology and geotechnical engineering is a function not only of the variability of the rock materials and their properties but also of the use to which the classification is put. Classification systems can be used either to simply characterize some particular rock property and thereby facilitate the application of information into a design (i.e., classification of rock strength by simple index tests) or relate findings to the determination of actual design parameters (i.e., tunnel support pressure).

(3) Classification systems have proven effective for the selection of underground opening support. The complexity of geology over the length of a tunnel drive means that even the best geologic surveys of the site for a proposed tunnel are unable to provide a complete understanding of the underground conditions. The optimum approach allows the design to be modified as information from the underground becomes available. Even once the ground is known, the final loading condition will only be known approximately and will probably vary along the tunnel length and be dependent on local geology and support performance. The main rock classification systems currently used to assist in the design of underground excavations are summarized in Table 4-4. A brief description of these systems is presented in the following. The use of these classifications for selection of initial ground support is discussed in Chapter 7.

(a) *Rock load method*. The application of a classification system determining tunnel support requirements for tunnels was first proposed in the United States by Terzaghi (1946), who developed a classification system for rock loads carried by steel ribs and lagging for a variety of rock conditions. The system is based on visual descriptions of rock conditions and can still be used for tunnels where steel sets and lagging are the method of tunnel support.

(b) *RQD*. RQD (Deere et al. 1967; Deere 1968) provides a quantitative index of fracturing within a rock mass based on the recovery of drill core. RQD is an empirical index. It is determined by counting all pieces of sound core over 100 mm (4 in.) long as recovery and expressing the recovery as a percentage of the total length drilled. RQD is expressed as follows:

$$RQD\ (\%) = (\text{length of core with pieces} > 100\ mm) \times 100/\text{length of core run}$$

The index is derived from standard-sized core at least 50 mm in diameter over lengths of borehole of at least 1.5 m (5 ft) in length. Although the degree of fracturing in a rock mass is a significant factor in determining tunnel support, other geologic conditions contribute to the performance of openings. These conditions include groundwater conditions, in situ stresses, fracture condition, fracture orientation, and opening size. RQD by itself does not provide a complete method for establishing tunnel support or standup times. RQD is, however, an essential element within the framework of other rock mass classification systems. It provides a quantitative index of rock quality in terms of fracture frequency that is easily obtained and has become an accepted part of core logging procedures. Most rock mass classification systems use RQD as a parameter to define fracture intensity of a rock mass. In combination with other parameters, an overall rating is established for the rock mass that reflects support needs and stand-up times for excavations. Table 4-5 shows the basic RQD descriptions.

(c) *Rock structure rating (RSR) concept*. RSR is based on an evaluation of conditions in 53 tunnel projects. It is a quantitative method for describing the quality of a rock mass and for selecting appropriate ground support, primarily steel ribs. Factors related to geologic conditions and to construction are grouped into three basic parameters, A, B, and C (Wickham, Tiedemann, and Skinner 1972; Skinner 1988). Parameter A is a general appraisal of the rock structure through which the tunnel is driven, determined on the basis of rock type origin, rock hardness, and geologic structure. Parameter B describes the effect of discontinuity pattern with respect to the direction of tunnel drive on the basis of joint spacing, joint orientation, and direction of tunnel drive. Parameter C includes the effect

Table 4-4
Major Rock Classification Systems Currently in Use (Barton 1988)

Name of Classification	Originator and Date	Country of Origin	Application
Rock Loads	Terzaghi (1946)	United States	Tunnels with steel supports
Stand-up Time	Lauffer (1958)	Austria	Tunneling
RQD	Deere et al. (1967) Deere (1968)	United States	Core logging, tunneling
RSR Concept	Wickham et al. (1972)	United States	Tunnels with steel supports
Geomechanics (RMR)	Bienawski (1979)	S. Africa	Tunnels, mines
Q-System	Barton et al. (1974)	Norway	Tunnels, large chambers

Table 4-5
Descriptions of Rock Quality Based on RQD (From Deere and Deere 1988)

RQD, percent	Description of Rock Quality
0 - 25	Very Poor
25 - 50	Poor
50 - 75	Fair
75 - 90	Good
90 - 100	Excellent

of groundwater inflow on the basis of overall rock mass quality, joint condition, and groundwater inflow. The RSR value of any tunnel section is obtained by summing the numerical values determined for each parameter. RSR is as follows:

$$RSR = A + B + C$$

The values for Parameters A, B, and C are given in Chapter 7 together with the estimate of support requirements in terms of an index, Rib Ratio (RR).

(d) *Geomechanics rock mass classification system*. The Geomechanics Rock Mass Classification System provides a quantitative method for describing the quality of a rock mass, selecting the appropriate ground support, and estimating the stand-up time of unsupported excavations. It is based on the summation of ratings for the following six rock mass parameters: strength of intact rock material, RQD, spacing of joints, condition and quality of joints and discontinuities, condition of groundwater, and orientation of joint or discontinuity relative to the excavation. The ratings for the parameters are provided in Appendix C.

(e) *Rock mass quality*. This system covers the whole spectrum of rock mass qualities from heavy squeezing ground to sound unjointed rocks. The system uses six parameters to describe the rock mass quality (Q) combined as follows:

$$Q = RQD / J_n \cdot J_r / J_a \cdot J_w / SRF$$

where

RQD = rock quality designation

J_n = joint set number

J_r = joint roughness number (of least favorable discontinuity set)

J_a = joint alteration number (of least favorable discontinuity set)

J_w = joint water reduction factor

SRF = stress reduction ratio

The three ratios that comprise the rock mass quality, Q, are crude measures of physical conditions defining the rock mass. RQD/J_n is a geometry index that can be considered as a measure of block size. J_r/J_a is a shear strength index that measures interblock strength. J_w/SRF is an external stress index and is a measure of the active stress. The range of values for the parameters are provided in Chapter 7.

f. Exploration and testing for gases in the ground.

(1) Gas sampling and testing during geotechnical explorations are required if gassy ground, either naturally occurring or contaminated, is suspected in the project area. Gaseous conditions must be identified in advance so they can be accounted for in the design and mitigated during construction. Several methods for gas testing are available. Some of the gases such as hydrogen sulfide or methane can be extremely toxic and/or explosive. It is important that professionals with experience in the methods and familiar with safety regulations, hazardous levels of flammable, explosive, and toxic gasses, and emergency response procedures for both workers and the public perform the testing and sampling.

(2) Exploratory drilling where there is a potential presence of methane, hydrogen sulfide, or other gases is commonly done by practitioners in the oil and gas industry and environmental geotechnical engineering.

g. Large-scale explorations.

(1) Many types of explorations can be classified as large-scale explorations. Some of these can be useful for underground works, but most are carried out for other purposes, as described in the following.

(a) Test pits and trenches are often excavated for foundation explorations, including dam foundations. They can be useful at tunnel portal locations, where drilling can be difficult and seismic surveys ambiguous.

(b) Test blasting is useful for quarry development.

(c) Test pumping is often carried out for deep excavations to determine overall permeability and probable yield of pumping for dewatering. It is often useful for shaft explorations and sometimes for tunnels in soft ground.

(d) Test grouting is useful for planning dam foundation grouting and has occasionally been useful when the designer has determined that grouting will be an essential part of a tunnel project (e.g., to avoid ground loss and deleterious settlement).

(e) Large-diameter boreholes (e.g., calyx holes) permit inspection of the borehole walls. Such boreholes have been successful for dam and power plant explorations in the past and may still be useful, though rarely carried out.

(f) Adits and pilot tunnels are frequently used for explorations of rock quality in dam abutments and foundations and for large tunnels and chambers. Such large-diameter explorations are necessary to conduct in situ tests such as flatjack, plate jacking, or radial jacking tests and helpful for other in situ tests. In addition to providing detailed geologic information, pilot tunnels permit evaluations to be made of the excavation effort, ground support needs, sensitivity of the rock to weathering, and other construction features. If excavated in the crown of a large excavation, a pilot tunnel can be used to drain formation water, provide a path for ventilation, permit prereinforcement of poor ground, and otherwise be helpful for the completion of the work.

(2) Extrapolations of ground behavior (especially conditions such as potentially squeezing ground), from the small scale of the pilot tunnel to the full prototype, must be accomplished with care due to the difficulty in selecting scale factors. Pilot tunnels should be considered, if not always carried out, for all large underground openings. Pilot tunnels have been carried out for the Peachtree subway station in Atlanta; highway tunnels in Glenwood Canyon, Colorado, and Cumberland Gap, Tennessee; and for highway H-3 tunnels on Oahu.

4-5. Presentation of Geotechnical Data

a. It is essential to make all geotechnical information available to the contractors who are bidding for the project. EM 1110-1-1804 sets forth principles and procedures for presenting geologic and geotechnical data in contract documents. Because of the volume and complexity of the complete exploration and testing documentation, it is not usually feasible or proper to incorporate all data in the contract documents. A selection of data to be presented in the contract documents must be made for each project, depending on the importance of the data. The remainder of the data would be available for review. At a minimum, all boring logs, test trenches, and adit data should be included in the contract documents.

b. A geotechnical design summary report (GDSR) may be included in the contract documents. This report presents the design team's best estimate concerning ground conditions to be encountered and how the geotechnical data has affected the design. This report becomes the baseline against which contractor claims for differing site conditions are gaged; it must therefore be written carefully and reviewed by people knowledgeable about the contractual use of this document. Further description of the use of the GDSR is found in ASCE (1991).

4-6. Geologic Investigations During Construction

a. Additional geotechnical information is sometimes required during the construction of the underground facility for one or more of the following purposes:

- Exploration ahead of the advancing face to discover regions of potential high water inflow, very poor ground, limestone caves, buried valleys, or dips in the weathering profile.

- Classification of rock mass to determine or verify initial ground support selection.

- Verification of conditions assumed for final tunnel lining design, including choice of unlined tunnel.

- Mapping for the record, to aid in future operations, inspections, and maintenance work.

b. Exploration ahead of the face is usually performed using a percussion drill to a distance greater than the typical daily advance. The advance rate of the drill is recorded. The drill is stopped from time to time to check the water flow into the borehole. If there is a possibility of encountering water under high pressure, drilling may have to be done through a packer, or the driller must be shielded against a high-pressure water jet.

c. Probehole drilling can often be accomplished during the period of blasthole drilling. When using a TBM, the machine usually must be stopped while drilling probeholes. Unless probehole drilling can be fitted into the maintenance schedule when the machine is stopped for other purposes, probehole drilling can reduce TBM operating time. If probehole drill steel gets stuck within the tunnel profile and cannot be recovered, then TBM advance can be severely hampered. It is, therefore, often the practice to drill over the crown of the TBM at a 3- to 6-deg angle from the tunnel axis.

d. If initial ground support is selected on the basis of ground conditions actually encountered, then a geologic appraisal is required after each round of blasting or more or less continuously for a TBM tunnel. A complete mapping in accordance with the Q method is tedious, time-consuming, and usually unnecessary. A simpler classification system, based on the characteristics of the geologic materials at hand, will usually suffice.

e. If mapping is required, it should be performed while the rock is still fresh and uncovered by debris, dust, or construction material. At the same time, the geologist should never venture into the heading of the tunnel before the heading is made safe. When initial ground support includes shotcrete placed by robot or consists of precast segmental concrete lining, mapping is not feasible. Methods of mapping are described in EM 1110-1-1804.